The uncertainties due to quark energy loss on determining nuclear sea quark distribution from nuclear Drell-Yan data

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Abstract

By means of two different parametrizations of quark energy loss and the nuclear parton distributions determined only with lepton-nuclear deep inelastic scattering experimental data, a leading order phenomenological analysis is performed on the nuclear Drell-Yan differential cross section ratios as a function of the quark momentum fraction in the beam proton and target nuclei for E772 experimental data. It is shown that there is the quark energy loss effect in nuclear Drell-Yan process apart from the nuclear effects on the parton distribution as in deep inelastic scattering. The uncertainties due to quark energy loss effect is quantified on determining nuclear sea quark distribution by using nuclear Drell-Yan data. It is found that the quark energy loss effect on nuclear Drell-Yan cross section ratios make greater with the increase of quark momentum fraction in the target nuclei. The uncertainties from quark energy loss become bigger as the nucleus A come to be heavier. The Drell-Yan data on proton incident middle and heavy nuclei versus deuterium would result in an overestimate for nuclear modifications on sea quark distribution functions with neglecting the quark energy loss. Our results are hoped to provide good directional information on the magnitude and form of nuclear modifications on sea quark distribution functions by means of the nuclear Drell-Yan experimental data.
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1 Introduction

The nuclear quark and gluon distributions have been one of the most active frontiers in nuclear physics because universal process-independent nuclear parton distribution functions are a key element in computing differential cross sections from nuclear collisions. The nuclear parton distributions directly affect the interpretation of the data collected from the high energy nuclear reactions[1,2], especially at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). The precise nuclear parton distribution functions are also very important in finding the new physics phenomena and determining the electro-weak parameters, neutrino masses and mixing angles in neutrino physics.

After the discovery of the EMC effect[3], it is well known that nuclear parton distribution functions are mutually different from those in free nucleon. The nuclear modifications relative to the nucleon parton distribution functions, are usually referred to as the nuclear effects on the parton distribution functions, which include nuclear shadowing, anti-shadowing, EMC effect and Fermi motion effect in different regions of parton momentum fraction. The origin of the nuclear effects is still under debate in theory, and it is considered that different mechanisms are responsible for the effects in the different regions of parton momentum fraction[4]. Up to now, almost all of the data on nuclear dependence is from charged lepton deep inelastic scattering experiments, which are sensitive to the charge-weighted sum of all quark and anti-quark distributions. From the charged lepton deep inelastic scattering off nuclei, the nuclear valence quark distributions are relatively well determined in the medium and large Bjorken x regions. However, the charged lepton deep inelastic scattering would not be sensitive to the nuclear sea quark distributions. In order to pin down the nuclear anti-quark distributions, it is desirable that the nuclear Drell-Yan reaction[5] is an ideal complementary tool in proton-nucleus collisions.

The nuclear Drell-Yan process is induced by the annihilation of a quark(anti-

quark) with a target anti-quark(quark) into a virtual photon which subsequently decays into a pair of oppositely-charged lepton. Therefore, the nuclear Drell-Yan process is closely related to the quark distribution functions in target nuclei. It is naturally expected that the nuclear Drell-Yan reaction, which is a complementary tool to probe the structure of nuclei in lepton-nucleus deep inelastic scattering, can be used to extract the sea quark distributions in the target nuclei. However, in high energy proton-nucleus scattering, the projectile rarely retains a major fraction of its momentum in traversing the nucleus. The quark and gluon in the induced proton can loss a finite fraction of its energy due to the multiple collisions and repeated energy loss in the nuclear target. In the view, the initial-state interactions are very important in nuclear Drell-Yan process since the dimuon in the final state does not interact strongly with the partons in the nuclei. The quark energy loss effect in nuclear Drell-Yan process is another nuclear effect apart from the nuclear effects on the parton distribution as in deep inelastic scattering.

In consideration of the strong necessities of precise nuclear parton distributions, the global analysis of nuclear parton distribution functions have been proposed in the recent years. So far, three groups have presented global analyses of the nuclear parton distribution functions analogous to those of the free proton. These are the ones by Eskola et al. (EKS98 [6−7] and EKPS[8]), by Hirai et al. (HKM[9], HKN04[10] and HKN07[11]), and by de Florian and Sassot nDS [12]. It is noticeable that EKPS and HKN employed Fermilab E772[13] and E866 [14] nuclear Drell-Yan data, EKS98 and nDS included E772 experimental data, and HKM proposed the nuclear parton distributions which were determined by means of the existing experimental data on nuclear structure functions without including the proton-nucleus Drell-Yan process.

In nuclear Drell-Yan process, the quark energy loss effect would lead to a degradation of the quark momentum prior to annihilation, further resulting in a less energetic dimuon. Therefore, the quark energy loss effect can drop the differential cross sections

as a function of the quark momentum fraction in the beam proton and target nuclei. We have investigated the nuclear Drell-Yan differential cross section ratios as the function of quark momentum fraction of the beam proton in the framework of Glauber model and two typical kinds of quark energy loss parametrization [15−17]. It is proved that there is quark energy loss effect in nuclear Drell-Yan reactions, which is an ideal tool to study the energy loss of the fast quark moving through cold nuclei. In the recent paper[18], a next-to-leading order and a leading order analysis are performed of the differential cross section ratios from the proton-induced Drell-Yan reaction off nuclei. It is found that the next-to-leading order corrections can be negligible on the differential cross section ratios for the current Fermilab and future lower proton energy. The Fermilab E866 experimental data were used in these works.

The nuclear Drell-Yan differential cross section ratios as a function of the quark momentum fraction in target nuclei are currently used to pin down the nuclear sea quark distribution functions. However, the quark energy loss effect can suppress the differential cross sections versus the quark momentum fraction. In order to obtained the precise nuclear sea quark distributions, the uncertainties due to quark energy loss should be carefully researched on determining nuclear sea quark distribution from Drell-Yan reaction off nuclei, which is the main purpose of this present paper. The Fermilab E866 measured the 800GeV proton incident Drell-Yan cross section ratios of per nucleon for Fe and W nuclei over Be. The impact of quark energy loss is canceled partly out in the Drell-Yan cross section ratios. The Fermilab E772 presented the Drell-Yan cross section ratios of various nuclei (C, Ca, Fe and W) versus deuterium in same energetic proton beam. Because the small nuclear effects in deuterium are neglected, the E772 experimental data help us to probe the quark energy loss effect in a more excellent way. In this paper, the studies on quark energy loss are extended to the E772 data. The influence of quark energy loss is quantified on the nuclear Drell-Yan differential cross section ratios. The uncertainties due to quark energy loss is elucidated on determining

nuclear sea quark distribution from nuclear Drell-Yan process.

The paper is organized as follows. In sect.2, a brief formalism for the Drell-Yan differential cross section and two different parametrizations of of quark energy loss are presented. The section 3 contains our results and analysis about the uncertainties due to quark energy loss on determining nuclear sea quark distributions. The summary is given in sect.4.

2 The formalism for Drell-Yan differential cross section

In the Drell-Yan process[4], the leading-order contribution is quark-antiquark annihilation into a lepton pair. The annihilation cross section can be obtained from the $q\bar{q} \to l^+l^-$ cross section, which is

$$\sigma[q\bar{q} \to l^+l^-] = \frac{4\pi\alpha_{em}^2}{9M^2}e_f^2,\tag{1}$$

where α_{em} is the fine-structure constant, e_f is the charge of the quark, and M is the invariant mass of the lepton pair. The nuclear Drell-Yan differential cross section can be written as

$$\frac{d^2\sigma}{dx_1dx_2} = \frac{4\pi\alpha_{em}^2}{9sx_1x_2}\sum_f e_f^2[q_f^p(x_1,Q^2)\bar{q}_f^A(x_2,Q^2) + \bar{q}_f^p(x_1,Q^2)q_f^A(x_2,Q^2)],\tag{2}$$

where $\sqrt{s}$ is the center of mass energy of the hadronic collision, x_1 and x_2 is the momentum fraction of the partons in the beam and target respectively, the sum is carried out over the light flavor $f = u, d, s$, and $q_f^{p(A)}(x,Q^2)$ and $\bar{q}_f^{p(A)}(x,Q^2)$ are the quark and anti-quark distributions in the proton (nucleon in the nucleus A).

The energy loss of fast partons in nuclei have been studied by Gavin and Milana [19], Brodsky and Hoyer[20], and by Baier et al.[21] respectively. Two typical kinds of quark energy loss expressions would be introduced with basing on the theoretical researches. One is rewritten as

$$\Delta x_1 = \alpha\frac{<L>_A}{E_p},\tag{3}$$

where α denotes the incident quark energy loss per unit length in nuclear matter, $< L >_A = 3/4(1.2A^{1/3})$fm[22] is the average path length of the incident quark in the nucleus A, and E_p is the energy of the incident proton. In addition to the linear quark energy loss rate, another one is presented as

$$\Delta x_1 = \beta \frac{< L >_A^2}{E_p}. \tag{4}$$

Obviously, the quark energy loss is quadratic with the path length. In what follows, the two different parametrizations are named to the linear and quadratic quark energy loss respectively. The quark energy loss in nuclei shifts the incident quark momentum fraction from $x_1' = x_1 + \Delta x_1$ to x_1 at the point of fusion. After considering the quark energy loss in nuclei, the nuclear Drell-Yan differential cross section can be expressed as

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha_{em}^2}{9sx_1x_2} \sum_f e_f^2 [q_f^p(x_1', Q^2)\bar{q}_f^A(x_2, Q^2) + \bar{q}_f^p(x_1', Q^2)q_f^A(x_2, Q^2)]. \tag{5}$$

With calculating the integral of the differential cross section above, the nuclear Drell-Yan production cross section is given by

$$\frac{d\sigma}{dx_{1(2)}} = \int dx_{2(1)} \frac{d^2\sigma}{dx_1 dx_2}. \tag{6}$$

The integral range is determined according to the relative experimental kinematic region.

3 Results and discussion

In the nuclear Drell-Yan experiments, the ratios are measured of Drell-Yan cross sections on two different nuclear targets bombarded by proton,

$$R_{A_1/A_2}(x_{1(2)}) = \frac{d\sigma^{p-A_1}}{dx_{1(2)}} / \frac{d\sigma^{p-A_2}}{dx_{1(2)}}. \tag{7}$$

The available nuclear Drell-Yan data are in the form of ratios over deuterium and beryllium, $R_{A/Be}(x_{1(2)})$ for the Fermilab Experiment866, and $R_{A/D}(x_{1(2)})$ for the Fermilab Experiment772, respectively. The x_1 dependence of cross section rations $R_{A_1/A_2}(x_1)$

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TABLE 1: The list of $\chi^2/d.o.f.$, α and β by fitting the E772 experimental data.

Exp. data	$\chi^2/d.o.f.(\alpha)$	$\chi^2/d.o.f.(\beta)$
$R_{A/D}(x_1)$	1.33 (1.26)	1.35(0.23)
$R_{A/D}(x_2)$	1.10 (1.31)	1.53 (0.23)

provide the best measure of the energy loss of the incident quarks in cold nuclear matter. The x_2 dependence of cross section rations $R_{A_1/A_2}(x_2)$ are used to complementarily obtain the nuclear sea quark distributions. In this work, by combining HKM cubic type of nuclear parton distribution with the quark energy loss, the global χ^2 analysis to the E772 experimental data are performed in the perturbative QCD leading order. $R_{A/D}(x_1)$ and $R_{A/D}(x_2)$ are respectively calculated and compared with the E772 experimental data on nuclear Drell-Yan differential cross section rations.

For the nuclear Drell-Yan differential cross section rations $R_{A/D}(x_1)$, the obtained χ^2 value is $\chi^2 = 234.36$ for the 122 total data points, The χ^2 per degrees of freedom is $\chi^2/d.o.f. = 1.92$ without quark energy loss effect. As for the rations $R_{A/D}(x_2)$, χ^2 value is $\chi^2 = 176.39$ for the 36 total data points, the χ^2 per degrees of freedom is given by $\chi^2/d.o.f. = 4.89$. It is apparent that theoretical results without energy loss effect deviate indeed from the E772 experimental data. After adding the fast quark energy loss effect on the ratios $R_{A/D}(x_1)$ and $R_{A/D}(x_2)$, the χ^2 per degrees of freedom, α and β are summarized in Table 1. for the linear and quadratic quark energy loss formula. It can be found that the theoretical results with energy loss effect are in good agreement with the experimental data. It is concluded that there is the quark energy loss effect apart from the nuclear effects on the parton distribution as in deep inelastic scattering. Meanwhile, the calculated $\chi^2/d.o.f.$ given by the linear quark energy loss is nearly the same as that from the quadratic quark energy loss for $R_{A/D}(x_1)$. The small differentness of $\alpha(1.26, 1.31)$ and same $\beta(0.23)$ value are obtained by fitting $R_{A/D}(x_1)$ and $R_{A/D}(x_2)$ data, which is different from the results with E866 data[18]. In fact, the

values of the parameter α (or β) in the quark energy loss expression should be the same for fitting the ratios $R_{A_1/A_2}(x_1)$ or $R_{A_1/A_2}(x_2)$ from the nuclear Drell-Yan experiment if the experimental data are sufficiently precise. Therefore, it is expected that the good α and β are determined from future precise nuclear Drell-Yan experiment. As an example, the calculated results with linear energy loss expression are shown in Fig.1 and Fig.2 against the E772 experimental data, which is the nuclear Drell-Yan differential cross section ratios for Ca to D and W to D as functions of x_1 for various interval of M, respectively. The solid curves are the ratios with only the nuclear effects on the parton distribution. The dotted curves correspond to the results from an linear quark energy loss with nuclear effect on structure function. In Fig.3, the computed ratios $R_{A/D}(x_2)$ are compared with the E772 data for C to D, Ca to D, Fe to D and W over D as functions of x_2, respectively. Apart from the same comments with Fig.1 and Fig.2, the dash curves stand for the results from the quadratic energy loss.

The calculated results above demonstrate that the quark energy loss effect suppress obviously the nuclear Drell-Yan differential cross section ratios versus the quark momentum fraction in target nuclei. In order to analyze the uncertainties due to quark energy loss on determining nuclear sea quark distribution, we quantify the quark energy loss effect on the nuclear Drell-Yan differential cross section ratios. The ratios $RR_{A/D}(x_2)$ on $R_{A/D}(x_2)$ without quark energy loss to those with linear quark energy loss ($\alpha = 1.26$) are calculated and tabulated in Table 2. The similar results can be obtained for the quadratic quark energy loss. The E772 and E886 cover respectively the ranges $0.1 \leq x_2 \leq 0.3$ and $0.01 \leq x_2 \leq 0.12$. For completeness, the ratios $RR_{A/Be}(x_2)$ are given for the E866 experimental data[18] in Table 3. It is shown that the suppression due to quark energy loss are approximately 2% to 3% for $R_{Fe/Be}(x_2)$ and 4% to 5% for $R_{W/Be}(x_2)$ in the ranges $0.03 \leq x_2 \leq 0.12$, respectively. As for the E772 experimental data in the ranges $0.1 \leq x_2 \leq 0.3$, the variations from quark energy loss are roughly 1% to 4% for $R_{C/D}(x_2)$, 2% to 8% for $R_{Ca/D}(x_2)$, 3% to 9% for $R_{Fe/D}(x_2)$, and 4% to 16%

TABLE 2: The ratios of $R_{A/D}(x_2)$ without quark energy loss to those with linear quark energy loss($\alpha = 1.26$).

x_2	0.04	0.10	0.18	0.24	0.30
$RR_{C/D}(x_2)$	1.010	1.014	1.023	1.030	1.037
$RR_{Ca/D}(x_2)$	1.022	1.030	1.049	1.064	1.078
$RR_{Fe/D}(x_2)$	1.026	1.036	1.058	1.076	1.093
$RR_{W/D}(x_2)$	1.045	1.062	1.100	1.131	1.161

TABLE 3: The ratios $RR_{A/Be}(x_2)$ from the E866 experimental data[18] with linear quark energy loss($\alpha = 1.27$).

x_2	0.03	0.05	0.07	0.09	0.12
$RR_{Fe/Be}(x_2)$	1.018	1.017	1.019	1.022	1.027
$RR_{W/Be}(x_2)$	1.038	1.036	1.040	1.045	1.055

for $R_{W/D}(x_2)$, respectively. It is found that the quark energy loss is canceled partly out in the proton-induced Drell-Yan cross section ratios for Fe to Be and W to Be from E866 data. The quark energy loss effect on $R_{A_1/A_2}(x_2)$ make greater with the increase of momentum fraction of the target parton. It is indicated that the heavier the target nuclei A, the bigger the uncertainties due to quark energy loss. The quark energy loss effect do not drop the nuclear Drell-Yan cross section in the same ratio. By taking account of the small energy loss effect, the $R_{C/D}(x_2)$ data in the region $x_2 < 0.1$ can be employed safely to determine the nuclear sea quark distribution functions. However, the remaining ones are not remarkably suitable for the constraints of the nuclear anti-quark distribution. The large degradation would result in an overestimate for nuclear modifications on sea quark distribution functions if the quark energy loss effect is not put in our mind. The suppression from energy loss would change not only the magnitude but also the form of nuclear modifications on sea quark distribution functions by means of the nuclear Drell-Yan experimental data because of the different compression ratio. We hope that our results from $RR_{A_1/A_2}(x_2)$ can provide good directional information on the nuclear modifications on sea quark distribution functions.

Let us now discuss the impact of the nuclear Drell-Yan experimental data on the global analysis of nuclear parton distribution functions. EKS98[6−7] used E772 data with the fitting done by eye only. The main improvements in EKPS[8] over the EKS98 are the automated χ^2 minimization, simplified and better controllable fit functions, and most importantly, the possibility for error estimates. EKPS parametrization is found to be fully consistent with the old EKS98 within the error estimates obtained. It is noted that EKPS include the E866 and E772 data in whole experimental kinematical range. The $\chi^2/d.o.f.$ is 0.916 (84.3/92) with fitting the nuclear Drell-Yan data. It is obvious that by reason of leaving the quark energy loss effect out, EKPS and EKS98 overestimate the nuclear modification on sea quark distributions. Therefore, the E866 collaboration gave a conclusion that the energy loss effect can be negligible in nuclear Drell-Yan reactions[14]. The HKN04[10] nuclear parton distributions , which is extended to HKN07[11], added E772 and E866 Drell-Yan data in the range $0.02 < x_2 < 0.2$. It is considered that the Drell-Yan cross section ratios is almost identical to the antiquark ratio $\bar{q}^A(x_2)/\bar{q}^{A'}(x_2)$ in $x < 0.1$ region. Our calculation on the ratios of $R_{A/D}(x_2)$ without quark energy loss to those with linear quark energy loss reveals that the maximum uncertainty from quark energy loss is approximately 3% for nuclei A(Ca,Fe)versus deuteron, and 6% for W over D at $x_2 \sim 0.1$. Because the effects of parton energy loss in the Drell-Yan process are neglected in HKN analysis, the nuclear modification is yet overestimated on sea quark distributions in Ca and Fe nuclei.

4 Summary

In this study, we have performed a leading order phenomenological analysis on nuclear Drell-Yan differential cross section ratios as a function of the quark momentum fraction in the beam proton and target nuclei for E772 experimental data. The quark energy loss effect is quantified on the nuclear Drell-Yan differential cross section ratios. The uncertainties due to quark energy loss is discussed on determining nuclear sea

quark distribution from the proton-induced Drell-Yan reaction off nuclei. With combining our previous works on the E866, it is concluded that there is the quark energy loss effect apart from the nuclear effects on the parton distribution as in deep inelastic scattering in nuclear Drell-Yan process. The quark energy loss effect on cross section ratios make greater with the increase of momentum fraction of the target parton. It is found that the heavier the nucleus A, the bigger the uncertainties due to quark energy loss. The proton incident middle and heavy nuclei Drell-Yan data result in an overestimate for nuclear modifications on sea quark distribution functions if the quark energy loss effect is neglected. It is hoped that our results would provide good directional information on the magnitude and form of nuclear modifications on sea quark distribution functions by means of the nuclear Drell-Yan experimental data. Because of the large experimental error in E866 and E772 experimental data, the parameter α and β can not be currently determined well. Therefore, we desire to operate precise measurements of the experimental study from the relatively low energy nuclear Drell-Yan process at J-PARC[23] and Fermilab E906[24]. These new experimental data on nuclear Drell-Yan reaction can shed light on the energy loss of fast quark propagating in a cold nuclei.

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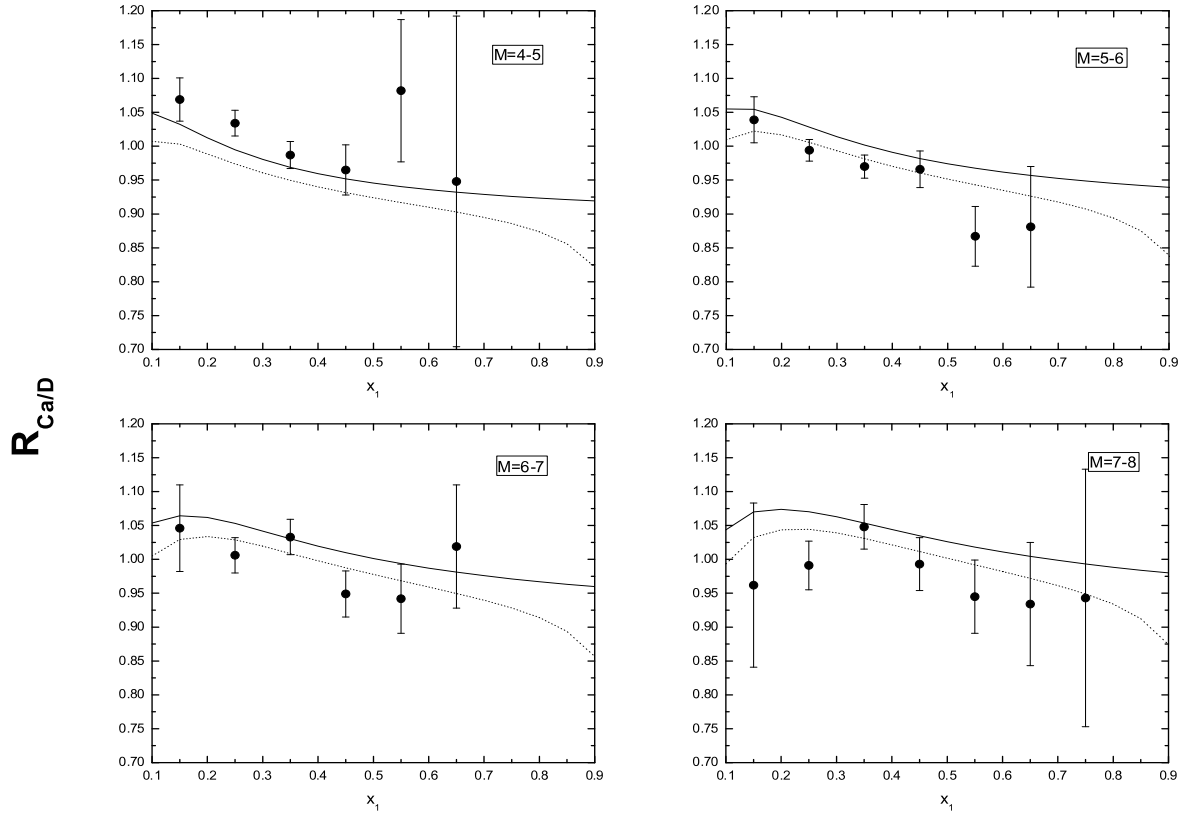
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FIG. 1: The nuclear Drell-Yan cross section ratios $R_{Ca/D}(x_1)$ for various intervals M. Solid curves correspond to nuclear effects on structure function. Dotted curves show the combination of linear quark energy loss effect with HKM cubic type of nuclear parton distributions. The experimental data are taken from E772[14].
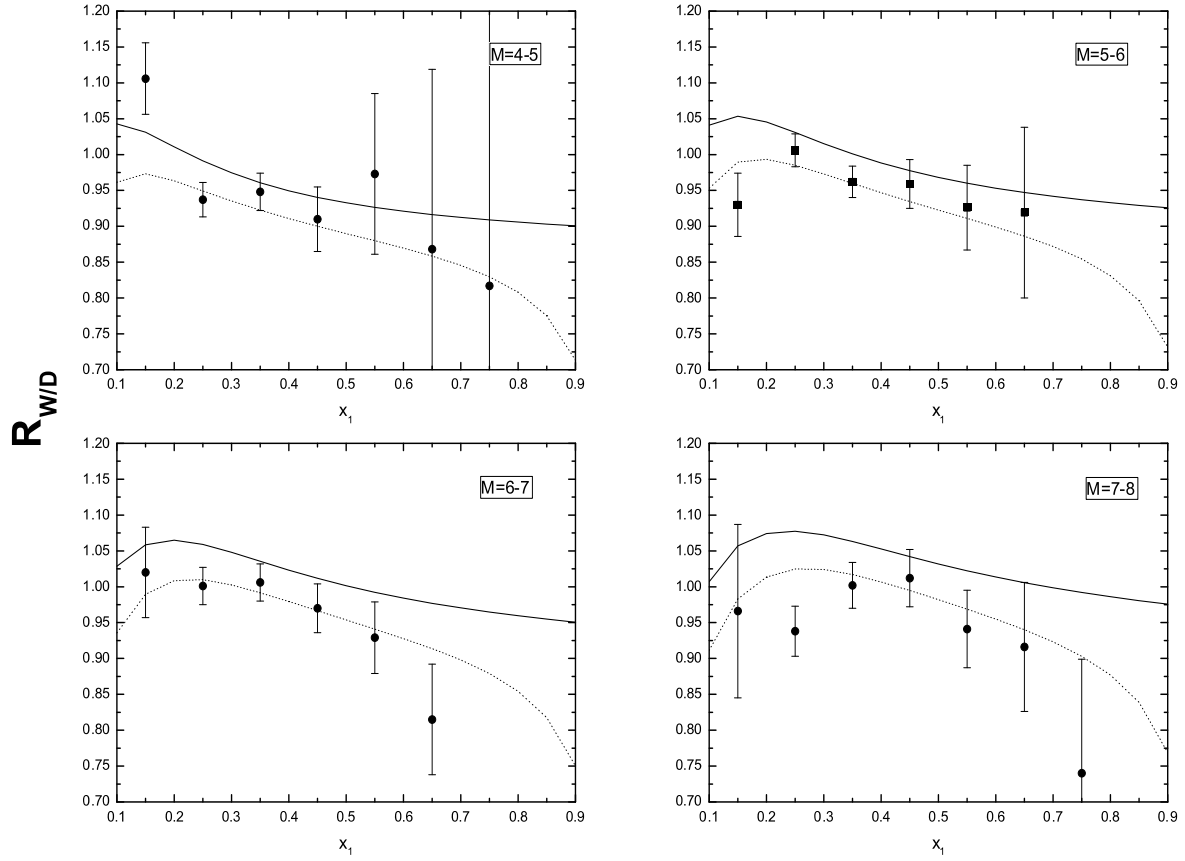
FIG. 2: The nuclear Drell-Yan cross section ratios $R_{W/D}(x_1)$ for various intervals M. The comments are the same as Fig.1
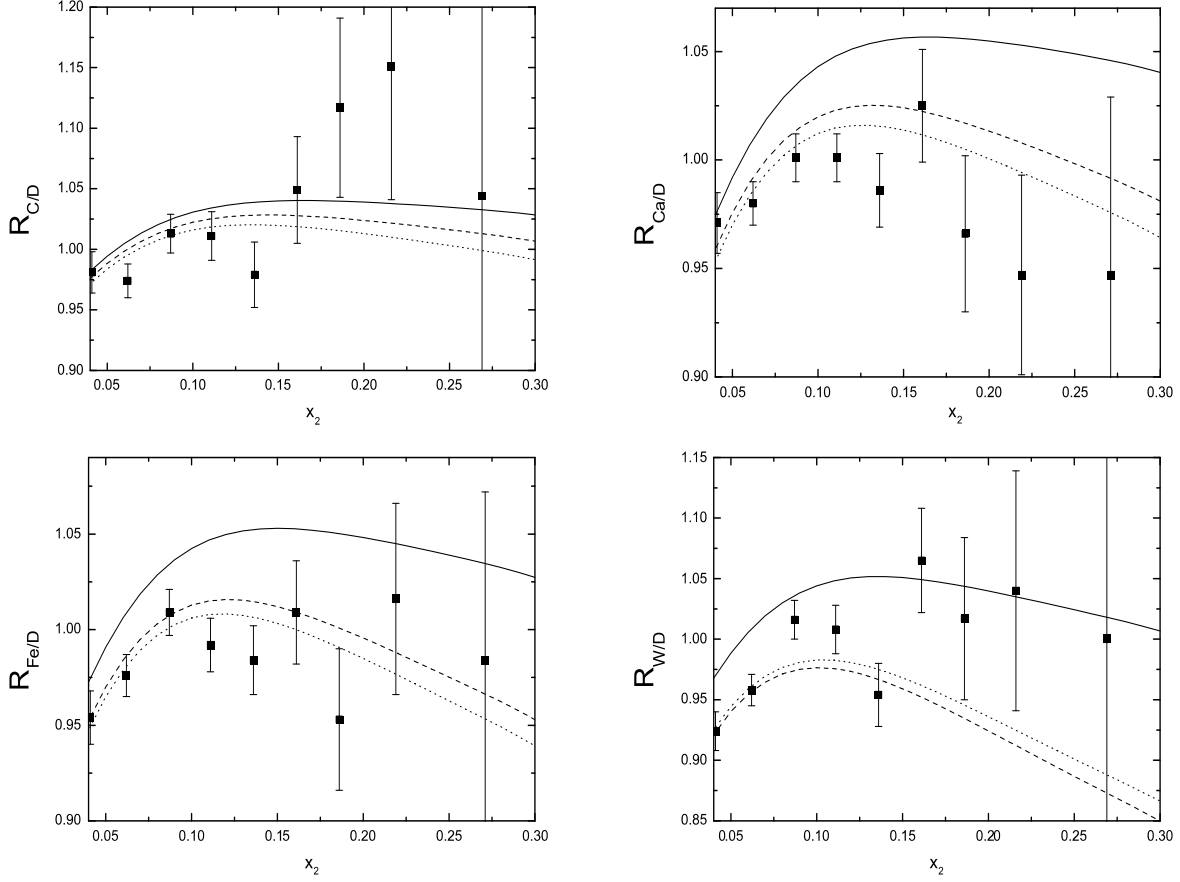
FIG. 3: The nuclear Drell-Yan cross section ratios $R_{A/D}(x_2)$ on nuclei(C,Ca,Fe,W) versus deuteron. Solid curves correspond to nuclear effects on structure function. Dotted and dash curves show the combination of HKM cubic type of nuclear parton distributions with the quark energy loss $\alpha = 1.26$ and $\beta = 0.23$, respectively. The experimental data are taken from E772[14].